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# A new approach for the calculation of the cut-off resolution parameter in bridging methods for turbulent flow simulation

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## ABSTRACT

The bridging HRL (hybrid RANS/LES) method is being increasingly used to solve complex and high-Reynolds number industrial flows. The increase in popularity is equally due to the conceptual simplicity and the potential ability to affect cut-off at an optimal length scale depending upon the problem on hand. In the bridging-type of HRL methods, the ratios of resolved-to-total kinetic energy and dissipation serve to partition the flow field into resolved and computational fields for reduced-order computations. Modeled transport equations for unresolved kinetic energy and dissipation equations are solved. In this paper, we develop an additional model transport equation to determine the resolved turbulent kinetic energy equation which enables an accurate and computational means of specifying the resolution control parameter for optimal computations. The proposed approach obviates the need for expensive averaging operations currently employed to compute the partition between resolved and modeled fields. This development will expedite the bridging HRL computations for flows with transient boundaries and moving geometries. The development is in the context of Partially-Averaged Navier–Stokes (PANS) model, but the conclusions are broadly applicable to other bridging HRL approaches. The advantage of the new approach is demonstrated for the flow past a square cylinder.

## 1. Introduction

The Reynolds-Averaged Navier–Stokes (RANS) turbulence models are still the most widely used for simulating complex industrial flows. However, in many modern applications with targeted error requirements, irrespective of the type of RANS turbulence model used, the turbulence closure model is the largest source of error. The Large Eddy Simulation (LES) approach has been increasingly used in recent years but its use is mostly restricted to research studies due to high computational costs. This has led to the development of scale-resolving simulations (SRS) such as hybrid RANS/LES (HRL) models, which in principle, provide a more affordable solution than LES while being more accurate than RANS. The scale-resolving simulations can be broadly classified as zonal and bridging (also called non-zonal) approaches. Bridging models employ the same closure model form (with continuously varying coefficients) in the entire domain without requirements for the interface between different modeling zones. These relatively simple models deliver more accurate results than conventional Reynolds-Averaged Navier–Stokes models provided the numerical mesh permits resolution and representation of large scales. The Partially-Averaged Navier–Stokes (PANS) formulated by Girimaji et al. (2003) and Girimaji (2006) is a bridging-SRS method that has shown promise in some recent computations of industrial flows (reference further below). The Partial-Integrated Transport-Modeling (PITM) of Chaouat and Schiestel (2005) shares many features in common with PANS. The most significant differences between the two methods are in the model coefficients in turbulence transport and the manner in which spatial changes in resolution are handled – Girimaji and Wallin (2013). There is a clear link between PANS and PITM methods which is well explained in the work of Foroutan and Yavuzkurt (2007) who use similar derivations for the main coefficient in the PANS method as done in the PITM, see also Chaouat (2017). At the current time, the PANS approach has been validated for a range of complex flows – see Krajnovic et al. (2012), Mirzaei et al. (2015), Jakirlic et al. (2016) etc. showing that the PANS method is ready for industrial use. Basara (2014) and Basara et al. (2016) demonstrate the utility of PANS in a variety of industrial flows.

The PANS closure model for unresolved scales is derived from the RANS model equations as a function of two resolution parameters: unresolved-to-total ratio of kinetic energy $f_k$ and unresolved-to-total ratio of dissipation $f_\varepsilon$. The PANS closure model coefficients change seamlessly from RANS values at one limit to zero at the other limit.

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**Nomenclature**

| | |
|---|---|
| $C$, $c$ | model constants with various subscripts |
| $f_k$ | unresolved-to-total kinetic energy ratio |
| $f_\varepsilon$ | unresolved-to-total dissipation rate ratio |
| $k$ | turbulent kinetic energy |
| $p$ | pressure |
| $P$ | production of k |
| $t$ | time |
| $u$ | velocity fluctuation |
| $U$ | resolved mean velocity |
| $V$ | instantaneous mean velocity |
| $\overline{v^2}$ | wall normal velocity scale |
| $\varepsilon$ | dissipation rate of k |
| $\nu$ | molecular kinematic viscosity |
| $\nu_t$ | turbulent eddy viscosity |
| $\zeta$ | velocity scale ratio ($\overline{v^2}$/k) |
| $\sigma_k$, $\sigma_\varepsilon$, $\sigma_\zeta$ | model constants |

*Subscript*

| | |
|---|---|
| u | unresolved quantity |
| ssv | scale supplying variable |

When the PANS closure coefficients go to zero, the resulting calculation is effectively DNS (direct numerical simulation). If the resolution parameters, $f_k$ and $f_\varepsilon$ are equal to unity, the PANS model reverts to the RANS model. It has been shown that in the cases with large-scale instabilities, the computed results improve substantially over the corresponding RANS model even when a few scales of fluctuating motions are resolved. At a higher level of resolution, the dependence of the solution on the mesh size (for given $f_k$) is much reduced when compared to the traditional Large-Eddy-Simulation (LES) results, see Basara et al. (2011). The first and original version of the PANS model was derived from the standard k-ε model. Two main additional variants of the PANS model have been derived to date, one based on the k-ω formulation (Lakshmipathy and Girimaji, 2006) and the one based on the k-ε-ζ-f model proposed by Basara et al. (2011).

Numerical meshes for most industrial applications are usually coarse near the wall so it is difficult to achieve the so-called wall-resolved Large Eddy Simulation (LES). This issue is present in PANS calculations as well: one could expect that $f_k$ is equal or close to unity near the wall which means that the RANS model is used there. This issue is more pronounced for a smooth surface separation rather than that from sharp edges. For example, the usage of the PANS k-ε model for the flow around 2D and 3D cylinders as shown in the work of Girimaji et al. (2003) and Krajnovic and Basara (2008), leads to late separation, like the results of the RANS k-ε model even though some fine-scale flow structures are captured. So, in general, the appropriate near-wall model could be very beneficial for PANS calculations. Therefore, the PANS variant based on the four equation near-wall eddy viscosity transport model, namely k-ε-ζ-f turbulence model is a further step to improve generality and accuracy of calculations and hence it is used in the work presented here. It must be noted that the k-ε-ζ-f model is the near wall model which can be used for any distance from the wall when used in conjunction with the wall treatment that combines integration up to the wall with wall functions. This model is a variant of the $v^2$-$f$ model (Durbin, 1991), the difference being that a transport equation for the wall-normal velocity scale ratio $\zeta$ ($= \overline{v^2}/k$, where $k$ is turbulent kinetic energy) is included rather than one for the velocity scale $\overline{v^2}$. The k-ε-ζ-f model has some numerical advantages over the original $v^2$-$f$ model but this is discussed elsewhere and will be not repeated here, see also original reference of Hanjalic et al. (2004).

In this work, we address the next step in the progression of PANS toward an accurate and easy to implement scale resolving scheme for complex flows. One of the key aspects of PANS computation is the specification of the resolution control parameters. In PANS computations, $f_k$ needs to be specified in accordance with the grid (Girimaji and Abdul-Hamid, 2005) and for high Reynolds number flows, $f_k$ can be taken to be unity. At the current time, there are two approaches to specifying $f_k$:

(i) $f_k$ can be specified using a precursor RANS simulation and local grid size (Girimaji and Abdul-Hamid, 2005);
(ii) Basara et al. (2008) proposed a dynamic update of the unresolved-to-total ratio of kinetic energy $f_k$ as a function of the mesh size and calculated length scales following the formula of Girimaji and Abdul-Hamid (2005). This approach was further explored in Basara et al. (2011), Krajnovic et al. (2012), Jakirlic et al. (2014) etc.

While the first approach is computationally viable, it is less efficient as it does not permit optimal use of grid resolution. The second approach is more computationally intensive as dynamic specification of $f_k$

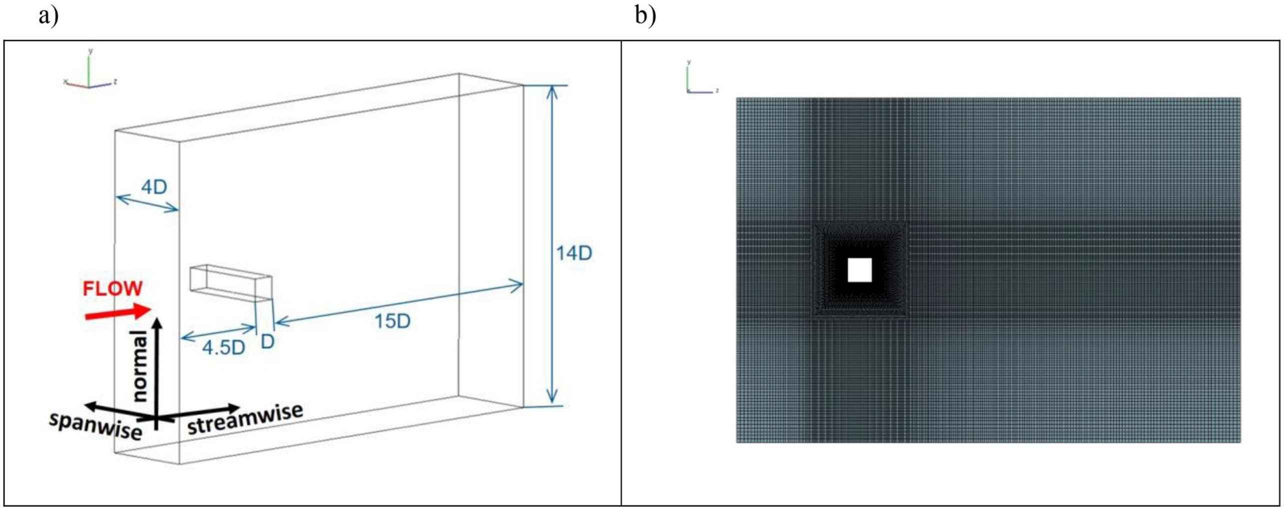

**Fig. 1.** Schema of the square cylinder case (a) and the computational mesh (medium: 2,294,240 cells) (b).